NASA TECHNICAL
MEMORANDUM

NASA TM X-64509

EXPERIMENTAL DEVELOPMENT PROGRAM FOR LUNAR SURFACE NAVIGATION EQUIPMENT

By Bobby F. Walls, William C. Mastin,
and Peter H. Broussard, Jr.
Astrionics Laboratory

April 30, 1970

NASA

George C. Marshall Space Flight Center
Marshall Space Flight Center, Alabama

TECHNICAL REPORT STANDARD TITLE PAGE

1. REPORT NO.	2. GOVERNMENT ACCESSION NO.	3. RECIPIENT'S CATALOG NO.
TM X-64059		

4. TITLE AND SUBTITLE

Experimental Development Program for Lunar Surface Navigation Equipment

5. REPORT DATE

April 30, 1970

6. PERFORMING ORGANIZATION CODE

7. AUTHOR(S)

Bobby F. Walls, William C. Mastin, and Peter H. Broussard, Jr.

8. PERFORMING ORGANIZATION REPORT #

9. PERFORMING ORGANIZATION NAME AND ADDRESS

George C. Marshall Space Flight Center
Marshall Space Flight Center, Alabama 35812

10. WORK UNIT NO.

11. CONTRACT OR GRANT NO.

12. SPONSORING AGENCY NAME AND ADDRESS

13. TYPE OF REPORT & PERIOD COVERED

Technical Memorandum

14. SPONSORING AGENCY CODE

15. SUPPLEMENTARY NOTES

Prepared by Astrionics Laboratory, Science and Engineering Directorate

16. ABSTRACT

An examination of some of the proposed schemes for manned lunar surface navigation is made with overtones of unmanned navigation requirements. The examination is made with the view in mind of actual near-term implementation with available and proven hardware. An outline of MSFC's efforts in this area is given, with particular emphasis on the present, ongoing in-house design, fabrication, and testing of a candidate dead reckoning system utilizing gyro references. The ability of this system to meet the requirements of simplicity, reliability, low cost, and ruggedness is discussed.

17. KEY WORDS

planetary surface navigation
odometer
processor
land locomotion

18. DISTRIBUTION STATEMENT

19. SECURITY CLASSIF. (of this report)	20. SECURITY CLASSIF. (of this page)	21. NO. OF PAGES	22. PRICE
Unclassified	Unclassified	23	$3.00

MSFC - Form 3292 (May 1969)

ACKNOWLEDGMENT

The authors express appreciation to Messrs. L. Michelbacher, J. Knickrehm, J. Folmar, and D. Henderson of the Sperry Space Support Division, Huntsville, Alabama, for their valuable contributions to this program.

TABLE OF CONTENTS

LIST OF ILLUSTRATIONS

TECHNICAL MEMORANDUM X-64509

EXPERIMENTAL DEVELOPMENT PROGRAM FOR LUNAR SURFACE NAVIGATION EQUIPMENT

SUMMARY

An examination of some of the proposed schemes for manned lunar surface navigation is made with overtones of unmanned navigation requirements. The examination is made with the view in mind of actual near-term implementation with available and proven hardware. An outline of MSFC's efforts in this area is given, with particular emphasis on the present, ongoing in-house design, fabrication, and testing of a candidate dead reckoning system utilizing gyro references. The ability of this system to meet the requirements of simplicity, reliability, low cost, and ruggedness is discussed.

INTRODUCTION

Since locomotion on the moon is an accomplished fact, increased attention is being paid to lunar surface navigation. This is evidenced by the recently negotiated contract on the manned lunar rover vehicle. However, studies and some tests on lunar navigation have been underway for several years. These studies have ranged from use of simple direction finders to sophisticated systems using satellite navigation. As to be expected, the suitability of the schemes has depended on the mission's constraints and requirements. The requirements, naturally, have been stringent in the areas of accuracy, simplicity, weight, reliability, ruggedness, and low power. These have combined to eliminate otherwise attractive navigation systems.

Principal emphasis here is on those requirements generally applicable to the manned lunar rover currently under study by NASA and private industry. Lunar rovers of this type are characterized by lightweight, small size, collapsibility for storage on the lunar module (LM), limited range, and relatively loose accuracy requirements. Some of the current efforts at MSFC in the design, fabrication, and testing of navigation systems generally applicable to short range, manned lunar vehicles are discussed in this report, with some discussion of longer range, unmanned navigation systems.

DISCUSSION

Navigation Requirements and Candidate Short Range Systems

Navigation systems considered are those lightweight, rugged, simple dead reckoning systems capable of acceptable accuracies on sorties of 30-km length and vehicle speeds of up to 20 km/hr. Nominal acceptable accuracies will be the following: direction to LM, within ± 3 deg at 5 km; distance to LM, to ± 500 m.

The stipulation that the system be a dead reckoning[1] system immediately narrows down the candidate types. Basically, by definition of dead reckoning, the present position must be extrapolated from a previously known position. By some means, position data in some coordinate system are obtained. This could be done, for example, with a strapdown system where position data are obtained by integration of accelerometer outputs. Such a system, where position information is available in all three axes, is marginally acceptable, if acceptable at all, for the following reasons: weight, complexity (sophisticated computer), thermal control (assuming fluid flotation), and lack of experience in strapdown systems. However, such a system certainly meets accuracy requirements.

A much simpler system is available as an alternative. This is the use of an odometric system for the measurement of distance and the use of a directional gyro to establish an inertial direction. Such a system has several inherent sources of error: the system assumes flat surface navigation because no provision is made for measuring anything but curvilinear distance; wheel slip is always prevalent to some degree; and gimbal errors arise from combined pitch and roll attitudes, giving erroneous yaw indications. With a knowledge of average terrain conditions, calibration in the system can compensate for the first sources of error mentioned. The addition of a vertical sensor can compensate for gimbal errors; e.g., vertical gyro. However, accuracy requirements can be met without incurring the additional weight, power, and complexity of a vertical gyro as indicated by previous studies [1].

---

1. A permissible deviation from dead reckoning is permitted in the case of updating the system output by simple landmark recognition (map-matching).

Inertial Reference

An inertial reference direction can be established in many ways; two of which have been chosen as lending themselves most practically to the navigation problem at hand. These are a simple directional gyro and a solar aspect sensor.

A directional gyro (a free gyro) consists basically of a spinning mass in a two-gimbaled system. Neglecting spurious torques, the spin axis maintains a fixed direction in space. In the practical case, torque is applied to maintain the spin axis normal to local vertical; e.g., by means of an electrolytic level. The primary purpose of a directional gyro is to give azimuth information; it is noted for simplicity and ruggedness, but not for lightweight, low power, and high accuracy. Directional gyros are not normally built to high accuracy specifications and have been used primarily in aircraft. However, accuracy is sufficient for this application.

Another approach is the use of a solar aspect sensor to provide an inertial reference, due compensation being made for the moon's rotation. Interest in the use of such optical means has decreased, commencing with the lunar dust problem encountered by the crew of Apollo 12. Many suggestions have been made for minimizing the dust adherence, but until more is known about the basic phenomenon, cures look doubtful. However, use of a solar aspect sensor is being investigated here.

Emergency Navigation

For the types of sorties discussed, consideration was given to simple types of emergency navigation. Providing bearing to the LM is available from a nondestruct display on the lunar rover, in the event of an inoperative navigation system or inoperative vehicle, it was concluded that adequate navigation could be performed with a sun compass or a variant of a sun compass. Results of sorties and laboratory tests are given in detail.

Test Vehicles

It was realized early in this program that an inexpensive, reliable vehicle would be needed as a test bed for the navigation systems. The vehicle would require better than average slope climbing ability (preferably without gear changes) and would roughly approximate a manned lunar vehicle. One of the more common all-terrain vehicles (ATV) was chosen for the test bed. It is a six-wheel vehicle powered by a two-cycle engine. The vehicle is being used as delivered except for addition of isolated mounting plates for inertial and optical equipment.

IMPLEMENTATION

Directional Gyro Approach

The test system was assembled using components that were immediately available or that could be acquired without excessive delay. This resulted in some component errors being greater than desired; however, because these errors were known, a meaningful experimental evaluation of the operational capabilities of such a system could be made.

The directional gyro package output is from a 3-wire, 400-Hz synchro transmitter (CX), illustrated in Figure 1. No provision was made for torquing the gyro, so a synchro differential (CDX) was used for aligning the gyro output to the initial reference and for updating.

A simple servoed synchro repeater provided the vehicle heading after proper alignment.

The sun is used as the azimuth reference. Sun sensors mounted on a theodolite and driving null meters measure the angle between vehicle heading and the solar subpoint, θ, to within one minute of arc. The angle between the sun and north, ϕ, is determined from the ephemeris. The use of north and east coordinates makes correlation between experiment position coordinates and map coordinates of the test area easier than correlation using a sun-based system. The vehicle heading was then $\gamma = -(\phi - \theta)$. The CDX shaft is rotated until this angle is registered on the heading display.

The output of the CDX excites a Scott-T transformer which converts the three-wire synchro output to the sine and cosine of γ. These two signals are then demodulated, filtered, and scaled so that a sine or cosine value of one is represented by a 10-Vdc level. For the hybrid system, the signals are then changed to digital form by an analog/digital converter for processing.

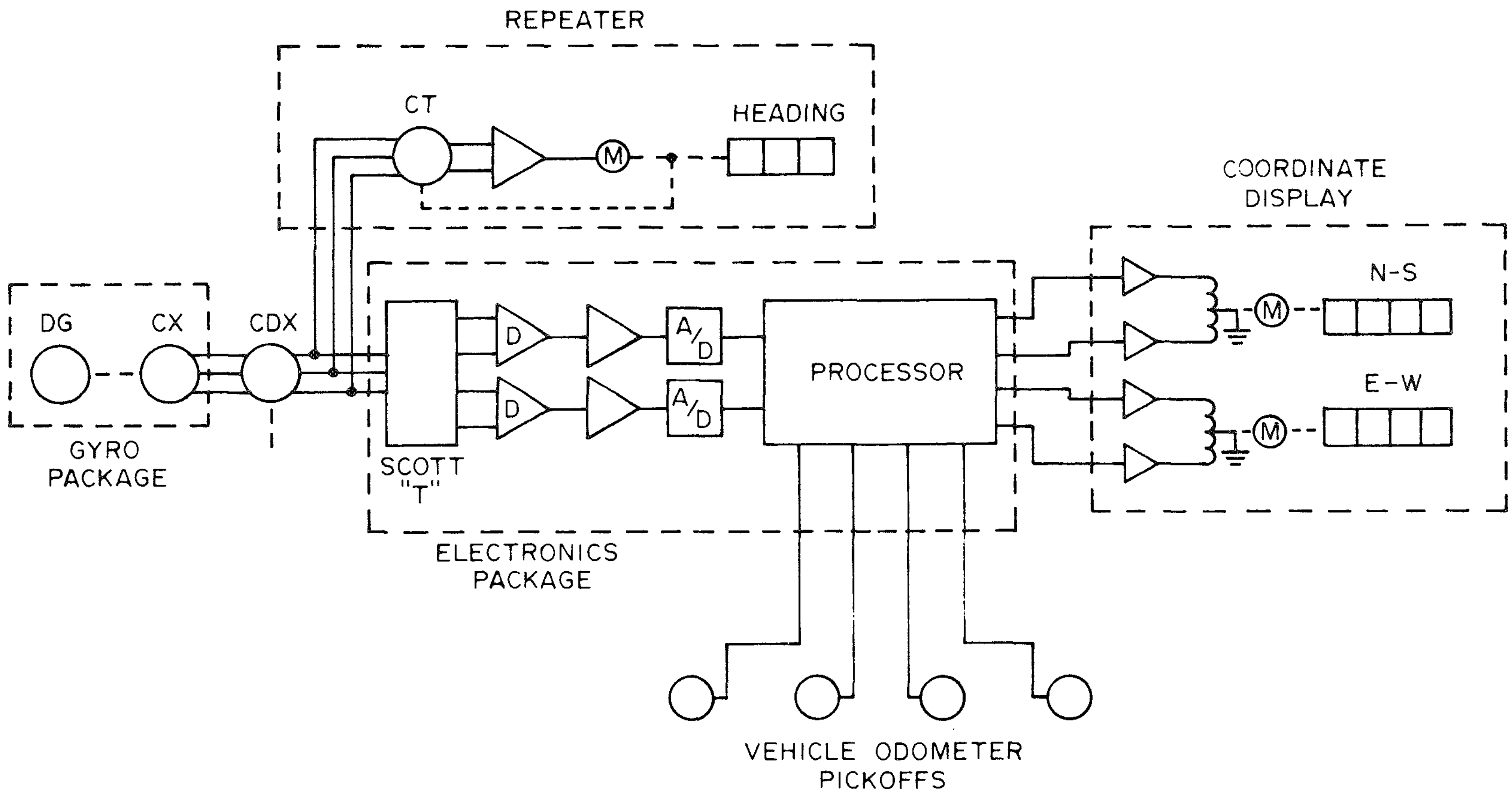

Figure 1. Hybrid coordinate resolver.

The functions performed by the processor, illustrated in Figure 2, are

$$\Delta X = \Delta S \text{ cosine } \gamma$$

$$\Delta Y = \Delta S \text{ sine } \gamma$$

and with proper scaling,

$$\text{northings} = \Sigma \Delta X$$

$$\text{eastings} = \Sigma \Delta Y \quad ,$$

where ΔS is an increment of distance. Note that the ΔX and ΔY terms do not contain a cosine (vehicle pitch angle) factor. Calculations based on an engineering lunar model surface [2] indicated that for a 30-km sortie on maria lurain, the error in total distance caused by neglecting this factor would be less than 100 m.

The ΔS increment is produced when the third fastest wheel odometer (magnetic reed switch) produces a signal. This method permits two wheels to spin without introducing an error. The system would also operate with the loss of the odometer signal from one wheel. The vehicle motion is measured more accurately and simply than with arithmetic averaging of the odometer pulses.

A voltage rise from an odometer produces a pulse whose width is determined by the delay times of three NAND gates and the value of a capacitor which sets a flip-flop. Further pulses from a wheel are ignored until the flip-flop has been reset. When odometer pulses have been received from any three wheels, a ΔS level is produced by an AND/OR combination. This level is sensed by the programmer, which accumulates the value of the sine and cosine of the heading angle existing at that time and resets the flip-flops.

The processor flow chart (Fig. 3) shows the series of operations occurring after the generation of a ΔS pulse. A shift register and an adder/subtractor unit are time-shared between the sine and the cosine inputs.

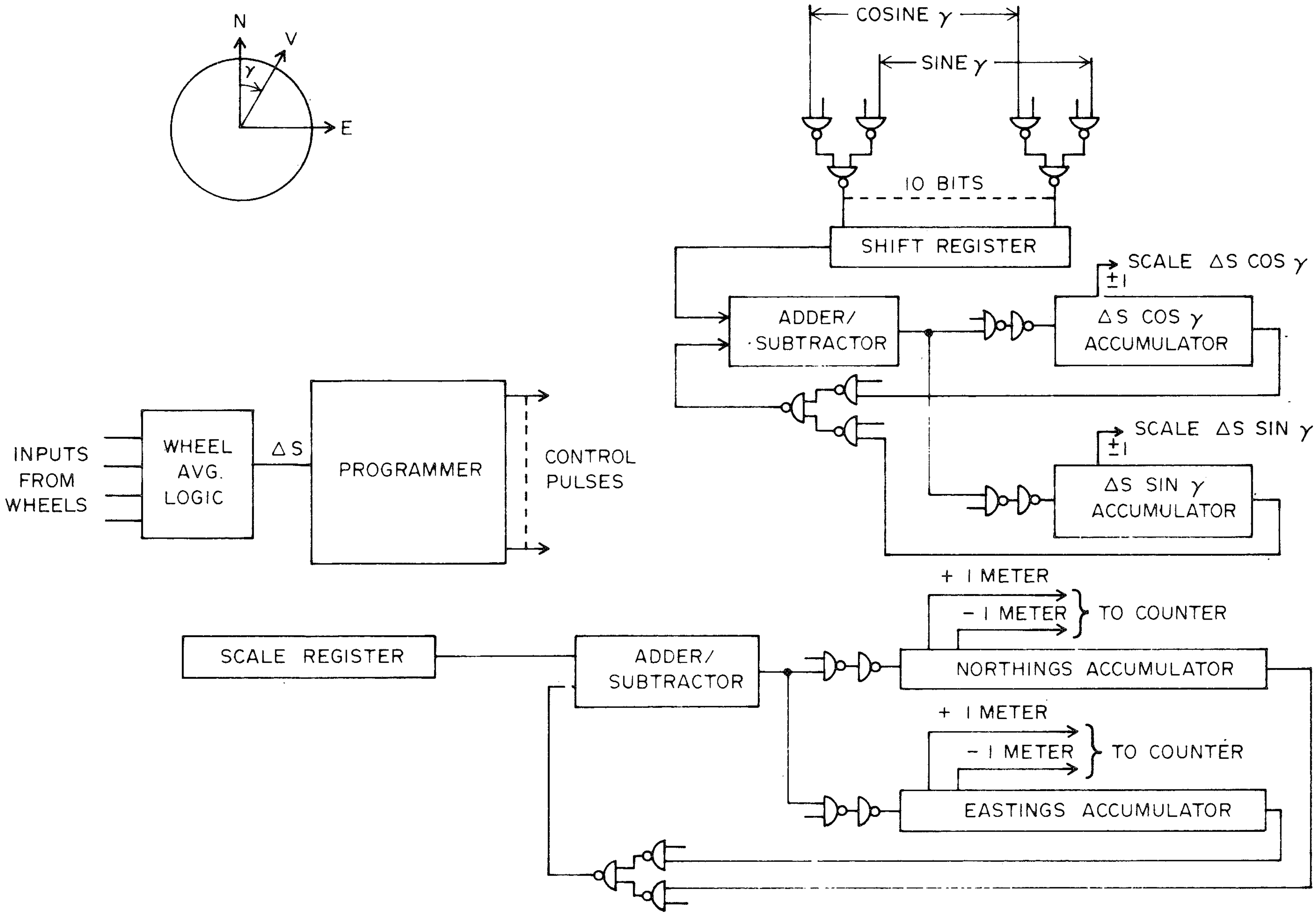

Figure 2. Processor.

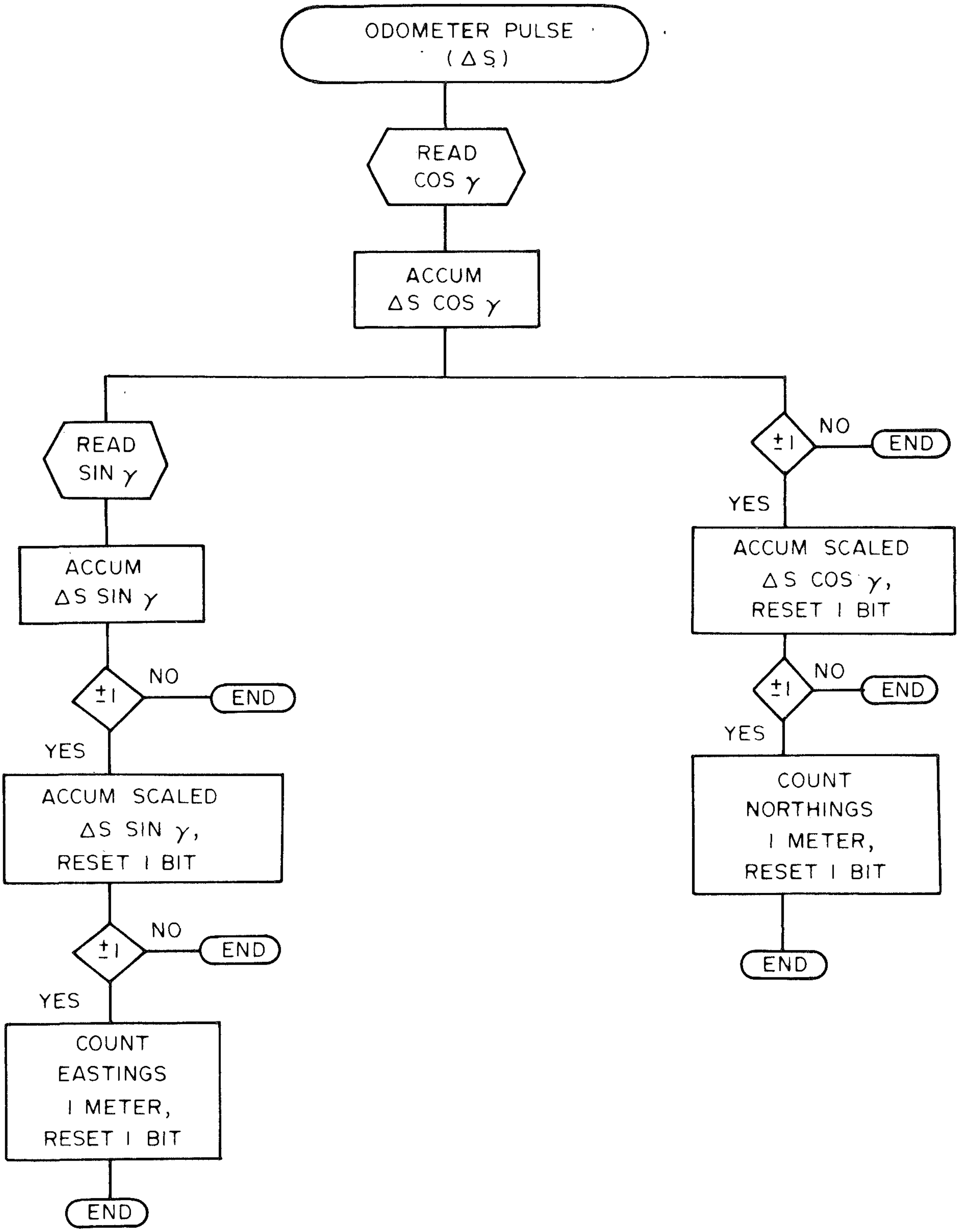

Figure 3. Processor flow chart.

The test vehicle wheel circumference is ~ 1.6 m. With two magnets mounted on each wheel, a ΔS pulse weight is ~ 0.795 m. This value, corrected experimentally before each test series, is preset into the scale register and added into the northings accumulator when $\Sigma \Delta S$ cosine γ reaches a value ≥ 1. At this time, one is subtracted from the ΔS cosine γ accumulator. A value ≥ 1 in the northings accumulator initiates a pulse which steps the north-south counter and resets the one bit in the accumulator to zero. Two's complements for negative numbers are used in the processing.

The east-west counter is updated in a similar way from the ΔS sine γ accumulator.

In the analog coordinate resolver system (Fig. 4), the demodulated, filtered, and scaled sine and cosine values are sampled by the pulse from the odometers. These constant width pulses, amplitude modulated by the sine and cosine values of the vehicle azimuth, are applied to the inputs of integrators. The integrators then drive an X-Y plotter, with the X input being

$$-\frac{\Delta T}{R_2 C_2} \int_0^T E \cos \gamma (t) \, dt$$

and the Y input being

$$-\frac{\Delta T}{R_1 C_1} \int_0^T E \sin \gamma (t) \, dt$$

The plotter then mapped the progress of the vehicle.

Solar Aspect Sensor Approach

An approach that would eliminate most moving parts is the use of solar aspect sensors in which the sun's rays pass through a slit onto a gray-coded sensor pattern. The output of the sensor is a binary number representing the angle between the sun vector and line perpendicular to the sensor's surface. The sensor packages to be investigated have two sensitive axes, azimuth and elevation, with a ±64-deg field-of-view for each axis and a nominal 0.5-deg resolution. Three such sensors will be mounted 120 deg apart for a 360-deg field-of-view in azimuth.

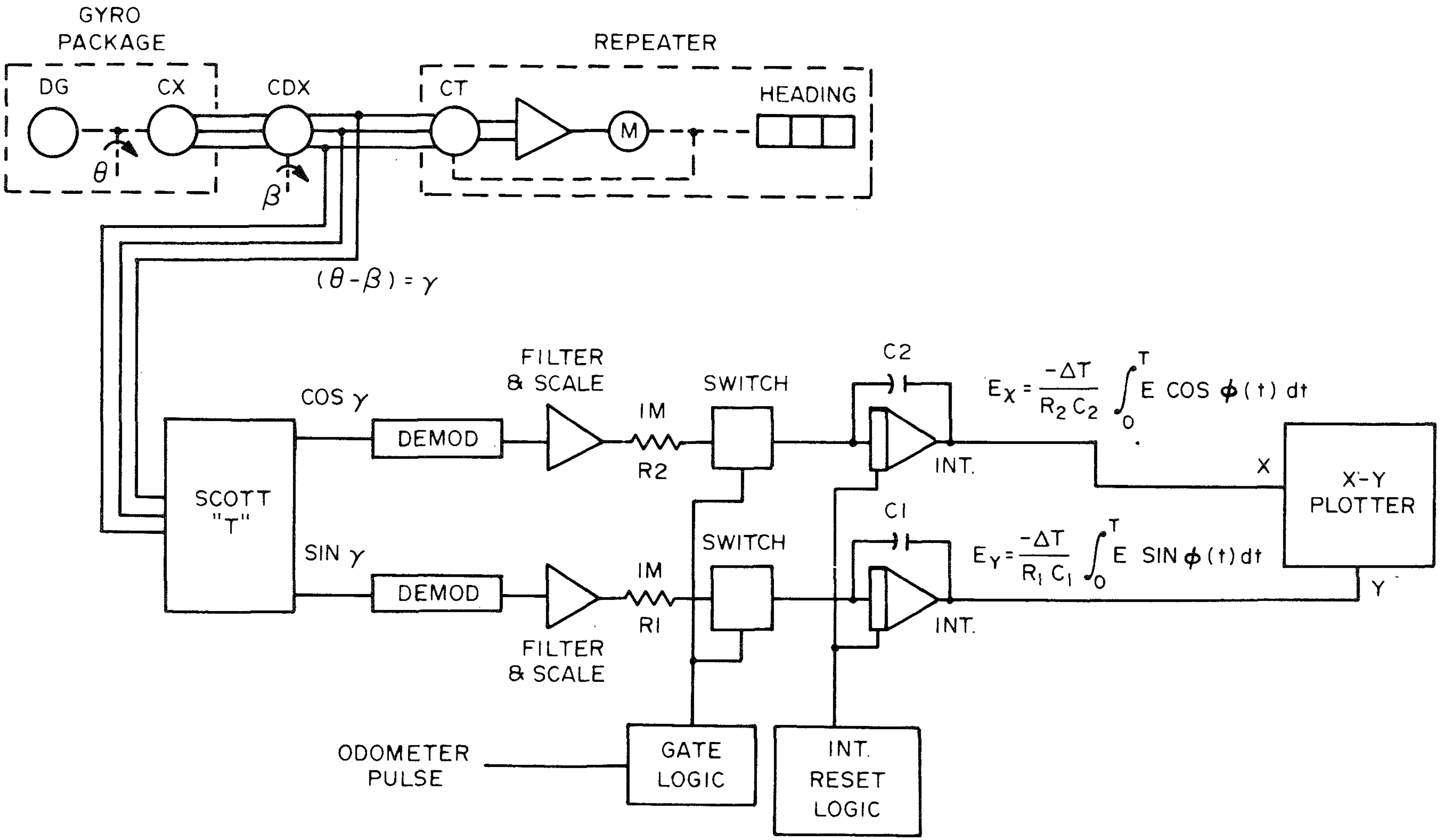

Figure 4. Analog coordinate resolver.

Because of refraction of the sun's rays inside the sensors, crosstalk between the azimuth and elevation readout is present and must be corrected. From Snell's law

$$\mu_c = \tan^{-1} \mu/\epsilon$$

where

μ = azimuth readout

ϵ = coelevation readout

μ_c = corrected azimuth readout.

In operation (Fig. 5), the gray-coded output of the sensor being illuminated by the sun must be selected and converted to binary. The corrected azimuth must then be computed; that is,

$$\mu_c = \tan^{-1} \mu/\epsilon \quad .$$

To get the total angle between the solar subpoint and the vehicle heading, θ, either 0 deg, 120 deg, or 240 deg must be added to μ_c. This step is due to the placement of the sensors on the vehicle. The angle between the solar subpoint and north, ϕ, determined from the ephemeris and stored beforehand is then subtracted from θ to yield γ, the vehicle heading from north. The sine and cosine of γ would then be obtained from memory or computed by one of the methods available, after which processing in conjunction with the odometer pulse would proceed as with the directional gyro.

For navigating a closed path, where immediate knowledge of lunar coordinates is unnecessary, the sun itself could be used as the basis for a coordinate system to simplify on-board processing. The position of the origin of a sortie would be known. Transformation of the coordinates of a position in a sun-based system to those in a lunar north-based system could be made later by the crew or on earth.

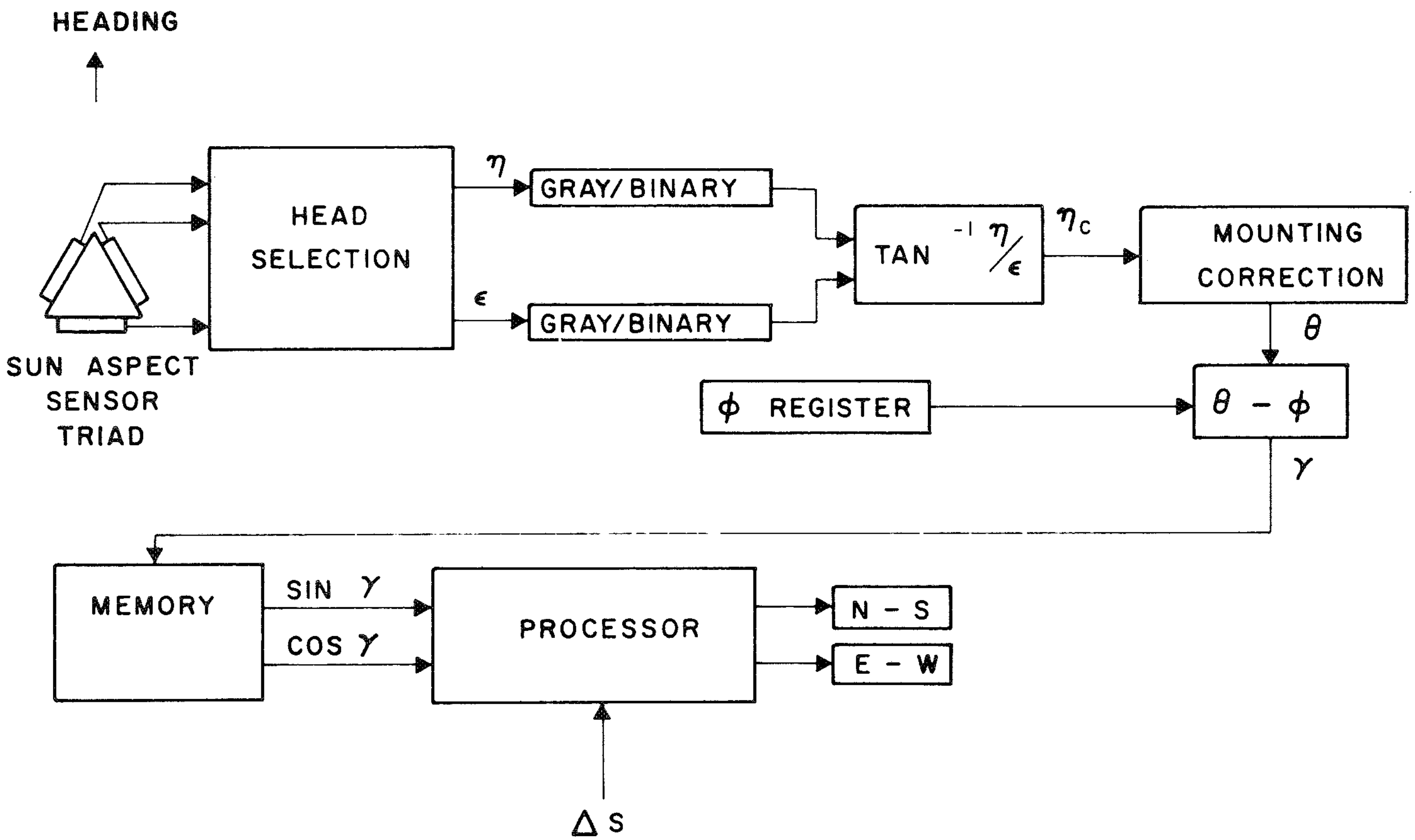

Figure 5. Sun sensor based, north referenced coordinate resolver.

PRELIMINARY TEST RESULTS

Emergency Navigation

A variant of a sun compass (Fig. 6) was used in simulated emergency sorties. The ground rules of the sorties were as follows. The test subject, equipped with the portable sun compass and a watch, was started at a known point on Redstone Arsenal with instructions to follow a specified heading. This heading, if followed without error, would lead to a target point located several kilometers away. This target point was unknown to the test subject, so target recognition was not a factor. The test subject was allowed, by use of the sun compass, to reestablish his direction of travel as often as he wished (subjects averaged about five). The subjects usually sighted on a prominent feature such as a bush, tree, etc. Table 1 shows the results of four sorties.

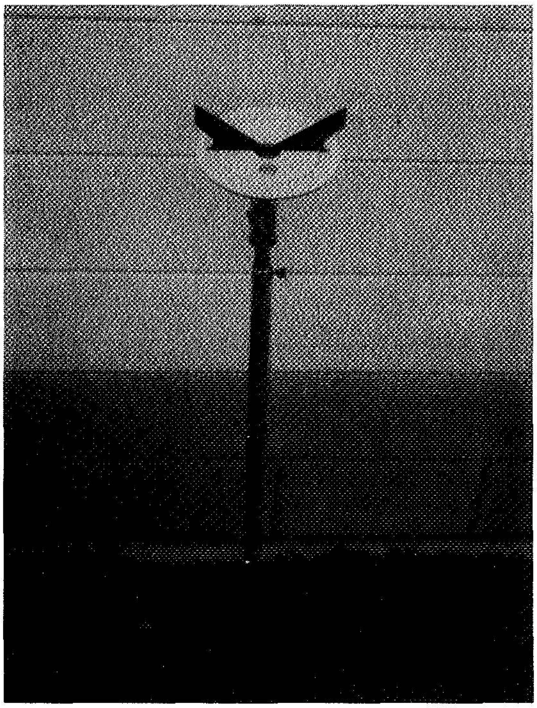

Figure 6. Sun compass.

These results are consistent with a simple analytical model derived here which, to a close approximation, relates the standard deviation of the lateral miss distance, σx, to the standard deviation of the sun compass angle error $\sigma_{\Delta\theta}$ by

$$\sigma_x = \sqrt{dr}\ \sigma_{\Delta\theta}$$

where d is the total distance of sortie and r is the distance between each reading. With the type of sun compass used, test results indicate that such a compass can be leveled and the heading can be read with a 3σ accuracy of 1.5 deg. The entire operation takes less than 30 sec.

TABLE 1. RESULTS OF FOUR SORTIES

Run	Individual	Length kilometers (mi)	Miss Distance meters (ft)	Time of Run (hr)
1	W. M.	3.3 (2)	107 (350)	1.5
2	J. B.	5.6 (3.5)	107 (350)	2.25
3	R. K.	5.6 (3.5)	69 (225)	1.9
4	D. H.	5.4 (3.4)	3 (10)	2.1

Inertial System

Full-fledged system tests and sorties are just beginning on this system; emphasis is being placed on the operational aspects. Successive designs will include such aspects as miniaturization, thermal, and other environmental control. While system test results are too widely scattered to form a coherent whole, all indications are that such a system is adequate for the accuracy requirements.

FUTURE SYSTEMS AND TESTS

In addition to the specific navigation systems described, several other systems are under development for possible use in lunar navigation. The directional gyro, odometer, and processor system described represent possibly the simplest inertial system possessing reasonable accuracy. A two-gyro system, consisting of a directional gyro and a vertical gyro, is being prepared for field tests, part of the objective being increased accuracy because of compensation for gimbal errors. Finally, mobile tests will be performed on a three-gyro strapdown system. Such a system as this is intended for long duration sorties for the unmanned mode.

Test vehicles for these programs include the ATV (Fig. 7) described previously (with TV camera and monitor for use in updating by landmark position fixing) as well as another ATV which is being outfitted for remote control. Control in the field will be accomplished from a 2.5 ton, 6X, electronic van. This van is also being outfitted with the necessary test gear, including computer, for the strapdown system.

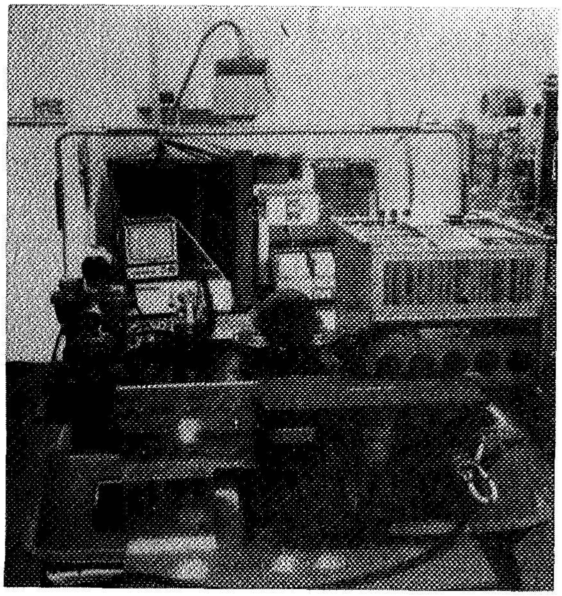

Figure 7. All-terrain vehicle.

REFERENCES

1. Lunar Navigation Study. Final Report, Vols. I and II, the Bendix Corporation.

2. Mason, R. L., McCombs, W. M., and Cramblet, D. C.: Engineering Lunar Model Surface. KSC-TR-83-D, September 4, 1964.

APPROVAL NASA TM X-64509

EXPERIMENTAL DEVELOPMENT PROGRAM FOR LUNAR SURFACE NAVIGATION EQUIPMENT

By Bobby F. Walls, William C. Mastin,
and Peter H. Broussard, Jr.

The information in this report has been reviewed for security classification. Review of any information concerning Department of Defense or Atomic Energy Commission programs has been made by the MSFC Security Classification Officer. This report, in its entirety, has been determined to be unclassified.

This document has also been reviewed and approved for technical accuracy.

Carl H. Mandel

CARL H. MANDEL
Chief, Guidance and Control Division

F. B. Moore

F. B. MOORE
Director, Astrionics Laboratory

DISTRIBUTION

NASA TM X-64509

INTERNAL

DIR

DEP-T

PD-AP-DIR
- Mr. Stewart
- Mr. Wagnon

PD-DO-DIR
- Dr. Thomason

PM-SAT-LRV
- Mr. Morea
- Mr. Belew
- Mr. Sisson
- Mr. Alter

S&E-DIR
- Mr. Richard

S&E-CSE-DIR
- Dr. Haeussermann

S&E-CSE-LRV
- Mr. Hamilton
- Mr. Arnett

S&E-P-LRV
- Mr. Davis

S&E-ASTR-DIR
- Mr. Moore
- Mr. Horton

S&E-ASTR-A
- Mr. Hosenthien
- Dr. Seltzer
- Miss Flowers

S&E-ASTR-C
- Mr. Swearingen

S&E-ASTR-E
- Mr. Aden

S&E-ASTR-G
- Mr. Mandel
- Dr. Doane
- Mr. Jones
- Mr. Doran
- Mr. Nola
- Mr. Broussard (30)
- Mr. Morgan
- Mr. Burch
- Mr. Walls
- Mr. Kelly
- Mr. Lee
- Mr. Kalange
- Mr. Caudle

S&E-ASTR-I
- Mr. Duggan

S&E-ASTR-M
- Mr. Boehm
- Mr. Thornton

S&E-ASTR-S
- Mr. Wojtalik
- Mr. Brooks
- Mr. Smith
- Mr. Davis
- Mr. Neudatschin

S&E-ASTR-R
- Mr. Taylor

S&E-ASTR-ZX

INTERNAL (concluded)

A&TS-MS-IL (8)

A&TS-MS-IP (2)

A&TS-MS-H

A&TS-PAT
Mr. Wofford

A&TS-TU (15)
Mr. Winslow

PM-PR-M

EXTERNAL

Scientific and Technical Information
Facility (2)
P. O. Box 33
College Park, Maryland 20740
Attn: NASA Representative (S-AK/RKT)

National Aeronautics and Space Administration
Washington, D. C. 20546
Attn: Mr. Jules Kanter, REG
Mr. Benjamin Milwitsky ~~REG~~ MA

The Boeing Company
220 Wynn Drive
Research Park Center
Huntsville, Alabama 35806
Attn: Mr. Henry Kudish
Mr. Erving Cope
Mr. B. E. Duchesneau (3)

United States Geological Survey
Flagstaff, Arizona 86001
Attn: Dr. George Ulrich
Mr. John Nuttall